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Geological conservation of natural and cultural heritage: the Italian experience in the 'Siq' of Petra

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The Petra Archaeological Park, a UNESCO World Heritage site since 1985, is characterized by a spectacular landscape but also by a great fragility fragile being prone to a diversity of natural risks (e.g. landslides, flash-floods, earthquakes) which can cause a potential danger to cultural heritage and visitors. The 'Siq', a natural canyon which constitutes the main entrance to the archaeological site, is among the most fragile areas of Petra due to its geological, geomorphological and geostructural characteristics. After the occurrence of rock falls occurred in the last decades, the UNESCO Amman Office in partnership with the Department of Antiquities of Jordan and the Petra Archaeological Park has therefore engaged in the 'Siq Stability Programme, a multi-year project, funded by AICS – Italian Agency for Development Cooperation. The project, presently in the 4th Phase of the Programme is mainly aimed at the analysis, monitoring and landslide mitigation works in the Siq of Petra. The paper resumes main characteristics of the project design and slope consolidation works of large blocks recently implemented with the fundamental support of Italian alpine climbers. A special attention has been provided non only to the works technical component but overall to the complex aspects of the logistics, site safety and use of the 'Siq' by tourists during the implementation of the works. Finally, the consolidation works in the 'Siq' of Petra represent a unique and challenging experience undertaken in a UNESCO World Heritage site in terms of technicality, continuous and positive cooperation and involvement of the local authorities and community engagement in the light of sustainable management of the cultural and natural heritage of Petra.

Keywords: *Rock slope consolidation, Risk Management, Petra Archaeological Park, UNESCO World Heritage site.*

1. Introduction

Reinforcement of natural or artificial slopes generally involve well-established methods, technologies, materials which are specifically designed and utilized according to site conditions and use. Nevertheless, usual civil engineering techniques and approaches adopted for consolidation of unstable slopes in UNESCO World Heritage sites have to provide, as much as possible, minimization of visual impacts and ensure at the same time a long-term effectiveness of the works. Following this fundamental prerequisite, the present paper reports the methods and the main results of slope consolidation works recently implemented in the 'Siq' of Petra (Jordan).

The World Heritage Site of Petra is located at ca. 200 km south of Amman, close to the town of Wadi Musa (Fig. 1). Petra was the capital city of the Nabataeans and became during Hellenistic and Roman times a major caravan centre and a crossroads for commerce in the Middle East. Petra is also worldwide known for the spectacular rock monuments carved in a multi-coloured sandstone landscape and the ingenious water management system which supplied the city, placed essentially in an arid environment. Nowadays, is one of the most visited archaeological site in the World and represent a fundamental cultural and also economical asset for Jordan. Petra, on the other hand, is also a very fragile site facing different climate-driven (e.g. flash-floods, wind erosion, weathering) and geological hazards (e.g. landslides, earthquakes) that constitute a permanent threaten for tourists and the long-term conservation of the monuments. In this regard, the 'Siq' of Petra, a 1.2 km naturally formed canyon that constitutes the main entrance to the archaeological site, present evidence of slope instability that has recently resulted in rock fall phenomena.

In line with the UNESCO Strategy for Risk Reduction at World Heritage properties (UNESCO, 2006), since 2009, the UNESCO Office in Amman has supported the Petra Archaeological Park and the Department of Antiquities, through the long-term 'Siq Stability Programme', funded by AICS (Italian Agency for Development Cooperation). The programme is addressed at assessing, managing and mitigating natural hazards in the 'Siq' with the final objective to develop a strategy towards prevention and mitigation of instability phenomena at the 'Siq' and, thus, further contribute to the management and conservation of the site. The 'Siq Stability Programme' incorporates different phases

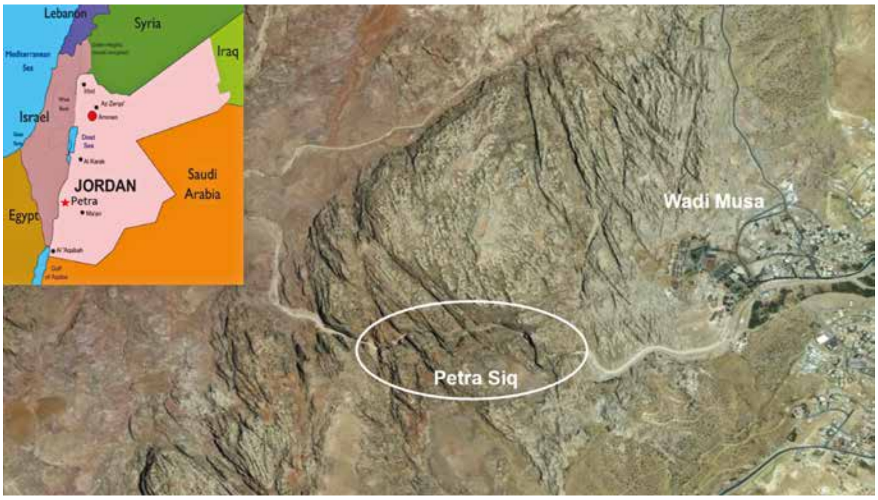

Fig. 1 – Location of the Petra archeological site and the 'Siq'.

Fig. 2 – UNESCO's 'Siq' Stability Programme methodological approach.

and projects. In 2009 a technical expertise in engineering geology was provided to the national authorities to support the consolidation of a large unstable block in the 'Siq'. The projects 'Rapid Risk Assessment' (2011) and 'Siq Stability' Phase I (2012-2015), were mainly focused on engineering geological analyses, the installation of an integrated monitoring system and a preliminary assessment of mitigation measures against rock instability (Delmonaco *et al*., 2013; 2014; 2015; Cesaro and Delmonaco, 2017; Cesaro *et al*., 2017). The subsequent Phase II (2015-2016) was aimed at the removal of potentially unstable small volume blocks and debris in the upper 'Siq' plateau and on the slope; this activity was undertaken by Jordanians workers and climbers in coordination with international experts (Delmonaco, 2016). The further step for the consolidation of larger potentially unstable blocks was planned after a detailed joint site survey carried out in cooperation with professional climbers. Specific guidelines and preliminary design for landslide risk reduction of the most critical areas in the 'Siq' were provided to UNESCO (Delmonaco *et al*., 2017a). In the Phase III and IV (2017-2021), slope consolidation works of large blocks were implemented by an Italian company under the supervision of UNESCO as the final stage, although not yet completed, of the methodological process illustrated in Figure 2. An outline and main results of such works are reported in the following paragraphs.

2. Geology and slope instability in the 'Siq'

The 'Siq' of Petra is a 1,2 km long and from 3 m to 15.70 m wide natural canyon characterized by very steep slopes with variable height from few meters at the entrance to several tens of meters in some areas of the path. The 'Siq' being one of the main channels of the Wadi Musa catchment, collects a series of lateral steep channels that convey superficial water during short and intense rainfall events causing quite frequent flash-floods (Fig. 3).

Geologically, the 'Siq' is prevalently formed by the Disi and Umm Ishrin Sandstone Formation (Cambrian-Ordovician) with a typical rupestrian and massive forms (Bender, 1974). The sandstone rock is mostly composed of medium-coarse grained, well-sorted quartz combined with highly variable proportions of cements consisting (Amireh, 1991) of authigenic kaolinite, hematite,


Fig. 3 – Flash-flood in the 'Siq'.


Fig. 4 – View of Al-Khazneh ('the Treasury').


Fig. 5 – Rock fall occurred in the 'Siq' in May 2015.

goethite and subordinate poikilotropic calcite (Amireh, 1991; Franchi & Pallecchi 1995; Franchi *et al*. 2009). The formation can be subdivided into three main units, according to their texture, mineralogical composition and engineering classification. The Upper Sandstone, called "honeycomb sandstone", is composed of white and mauve-red, coarse to medium grained, hard and massive sandstone, capable to promote very steep slopes. It is characterized by typical cavernous weathering caused by solution of cement and consequent granular disintegration that form the typical honeycomb structures. The Middle Sandstone ("tear sandstone") consists of multi-coloured, medium to fine-grained, well-bedded and friable sandstone. Weathering is diffuse, especially by solution of the ferruginous and manganesiferous layers and cements that cause change or the rock face from red-brown to yellow and grey. Cross-bedding structures and presence of interbedded silty and clayey sands are quite common. This unit, due to anisotropy of materials, sensitive to moisture change, can promote sliding of blocks especially under saturation conditions. The Lower Sandstone ("smooth sandstone") is made of white, medium to coarse-grained, hard massive sandstone, mainly used as building and decorative sandstone. The majority of the rock monuments of Petra were almost entirely cut in the Umm Ishrin formation due to its good mechanical strength and facility to hand-carving (Amireh *et al*., 2001) (Fig. 4).

The geomorphology of the 'Siq' is the result of long and short-term factors such as tectonic uplift, erosion due to runoff, differential erosion and weathering of sandstone rocks. The mainly E-W orientation of the 'Siq' and its meandering course are a consequence of the intersection of sub-vertical faults and master joints. Along with main tectonic structures, other discontinuities in the 'Siq' rock slopes are sub-horizontal bedding planes and joints, from vertical to medium slope angle which correlated with the geomorphological evolution of the 'Siq'. Slope instability processes are conditioned by local orientation, density and persistence of discontinuities, and can affect rock blocks with variable dimension depending on types and degree of structural control. The main rock slope instability phenomena are: a) fall of loose debris (very small blocks) from the cliff edges and terraces triggered by heavy rainfall and flash-floods; b) fall/toppling/sliding of small/medium and large size blocks along pre-existing discontinuities of the rock mass. Slope failures in the 'Siq' of Petra generally occur along pre-existing discontinuities and their triggering is mostly associated with short-term factors depending mainly on climatic parameters (i.e. temperature/humidity changes) and seismicity factors (Delmonaco *et al*., 2013; 2014). In the last two decades, several landslide events, mostly rock falls and rock slides, with variable magnitude (volumes from < 1 m^3 to > 10 m^3) have occurred in the 'Siq' (2009, 2015) and in the core area of the site (2009, 2010, 2016, 2020) (Fig. 5). A brief description of such events is summarized in Table 1.

In Petra, heavy rainfall precipitation is characterized by an average yearly recurrence of 4-5 events, from October to early May, characterized by high intensity and short duration; these events can cause removal and fall of loose debris from the upper slopes and outlets of secondary channels (Delmonaco, 2016).

Based on available meteorological records and recent rock failures inventory, in the 'Siq' of Petra it is possible to estimate a yearly return time TR for debris fall as TR =4÷5 /yr whereas for rock slope failures (rock fall, rock slide) the return time can be assumed as TR =0.1÷ 0.2/yr (Delmonaco, 2016; Delmonaco *et. al*., 2017b).

Tab. I – Inventory of recent landslide events in Petra.

Location	Date	Typology	Magnitude
Siq (sector 11)	01.05.2009	Rock fall	0.025 m^3
Wadi Mu'eissra (Tomb 609)	01.03.2010	Rock-slide	70÷80 m^3
High Place of Sacrifice	14.10.2010	Rock fall	10÷15 m^3
Siq (sector 11)	29.05.2015	Rock fall	3÷4 m^3
High Place of Sacrifice	13.04.2016	Rock slide	1.5÷2.0 m^3
Treasury Plaza	19.02.2020	Rock fall	0.025 m^3

Rock slope deformation of largest unstable blocks in the 'Siq' were assessed through a wireless monitoring system installed in 2013, functioning until 2016 (Fig. 6). The wireless monitoring system was composed of 2 wire deformometers, 2 crack deformometers and 2 tiltmeters, 6 air-temperature sensors, a meteorological station, with wireless technology sensors for on-time registration and transmission of data. Displacement of the main fractures, inclination of the blocks and meteorological parameters were the main data collected by the system and sent to a main server via GPRS through a gateway located in the upper 'Siq' in front of the 'Treasury' monument. Data can be visualized on-time and further analysed through a specific software developed by EASA®.

Monitoring data during the 3-years observation have shown the dominant role of temperature in joints displacement where opening and closure of joints are strongly correlated with air cooling and heating (Fig. 7). A further analysis on the role of daily temperature oscillation in Petra in relation with recent rock falls suggest the value of ca. 15° in daily temperature difference as a possible threshold capable to promote rock failures in the' Siq' and Petra Archaeological Park Delmonaco *et al*., 2017b) (Fig. 8).

3. Consolidation works in the 'Siq'

3.1. Rationale

The engineering geological study conducted during the Phase

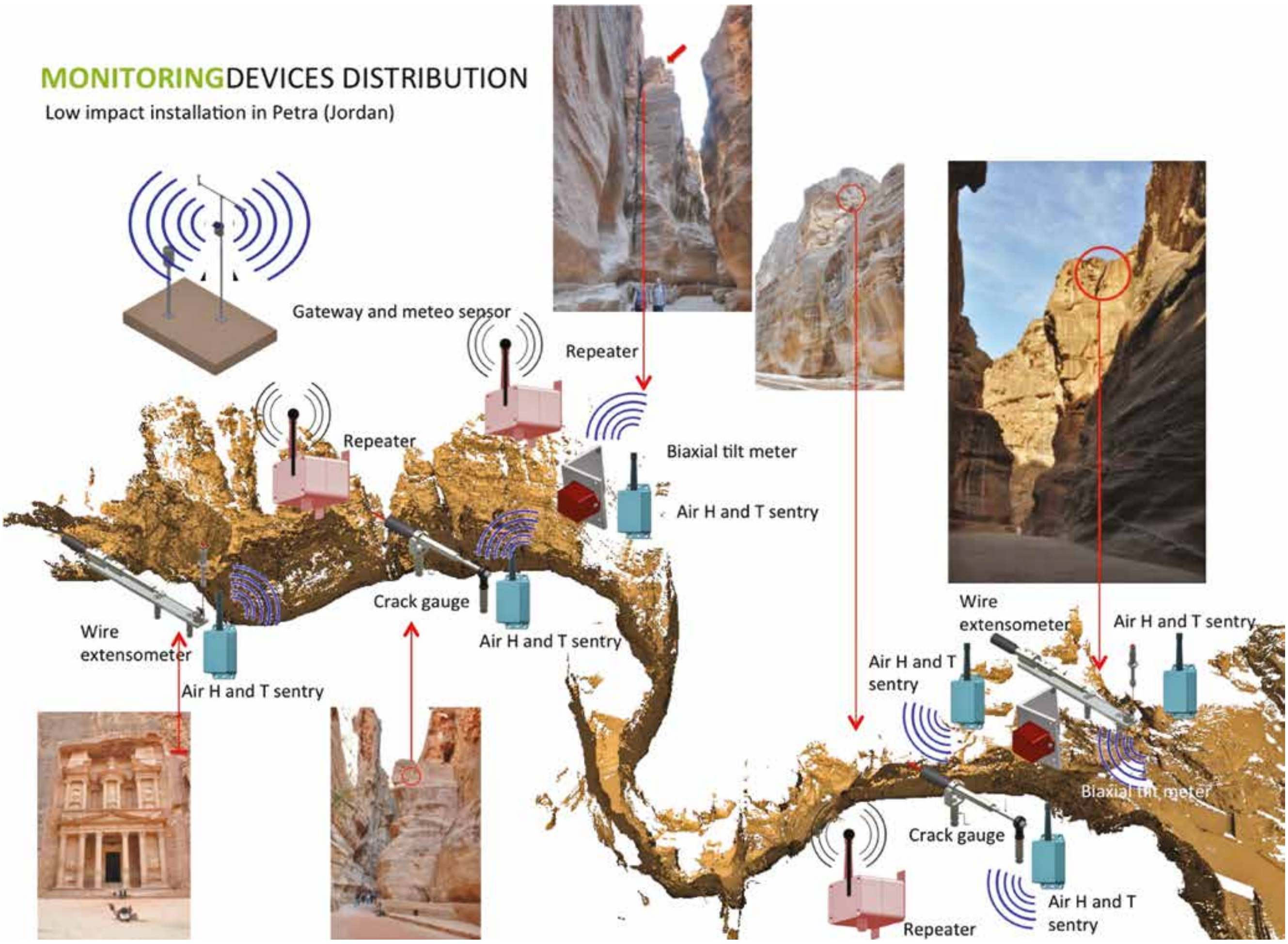

Fig. 6 – Scheme of the wireless monitoring system installed in the 'Siq' in 2013 in the UNESCO 'Siq Stability Project, Phase I.

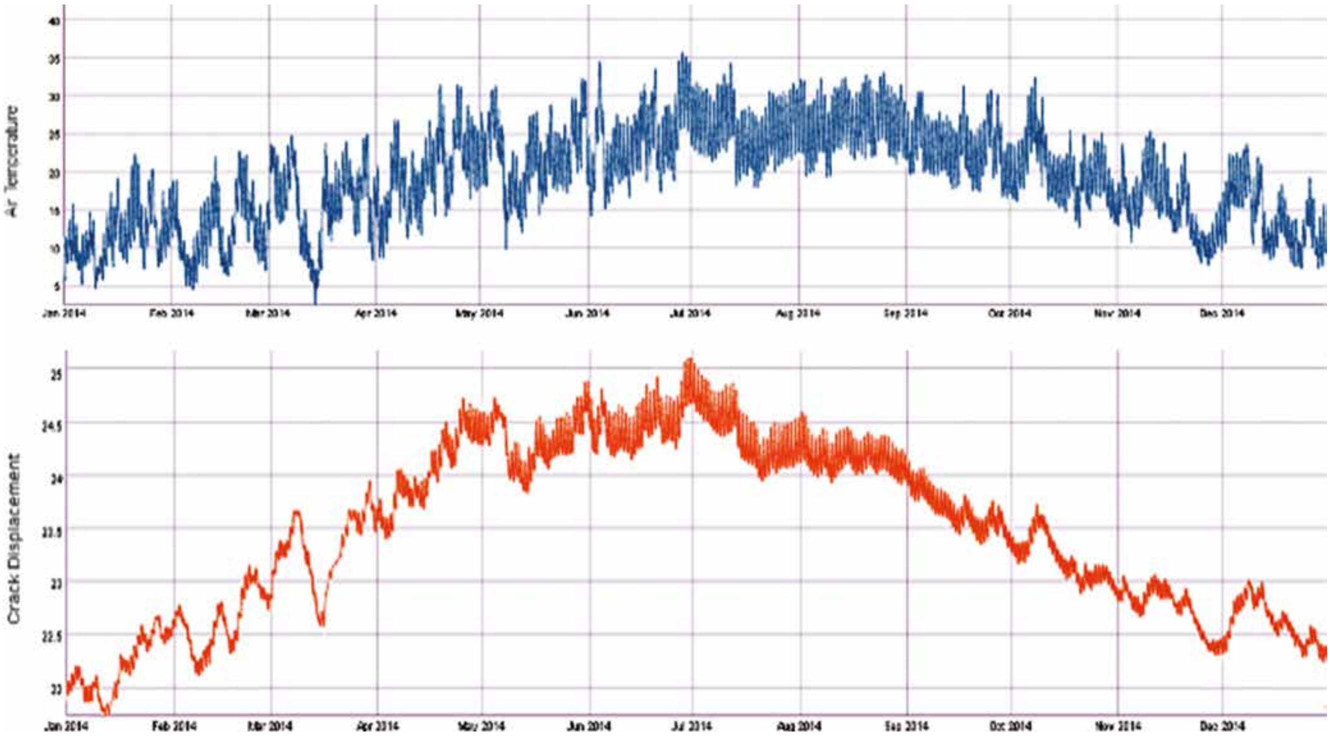

Fig. 7 – Correlation between air T° (up) and crack deformation measured in a rock block in the 'Siq'.

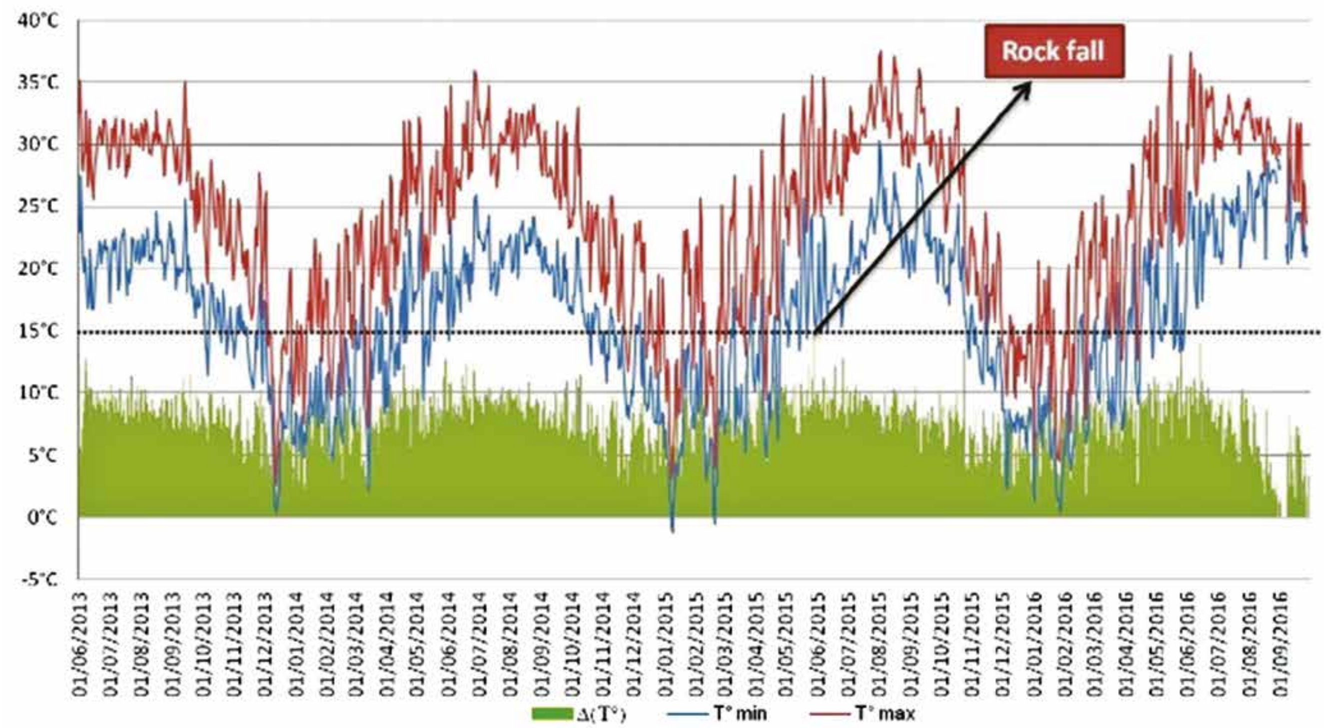

Fig. 8 – Possible threshold value (ca. 15°) correlated with air T° daily difference and rock fall occurred on May 31, 2015.

I of the UNESCO 'Siq Stability Project' by ISPRA defined and mapped most of the potentially unstable rocks outcropping along the 'Siq' slopes. The 'Siq' was divided into 14 sectors, according to the main local orientation of the path. A further and more detailed slope inspection, as part of the Phase II of the Project, was successively conducted in 2016 in the 'Siq' by Assoroccia and ISPRA with climber techniques. A series of potentially unstable zones prone to rock fall and debris flows, some of them not recognised during the previous studies, were detected and documented with detailed guidelines and preliminary design projects aimed at consolidation or mitigation of in-

Fig. 9 – Consolidation of a rock block in the 'Siq' sector 9 (2019).

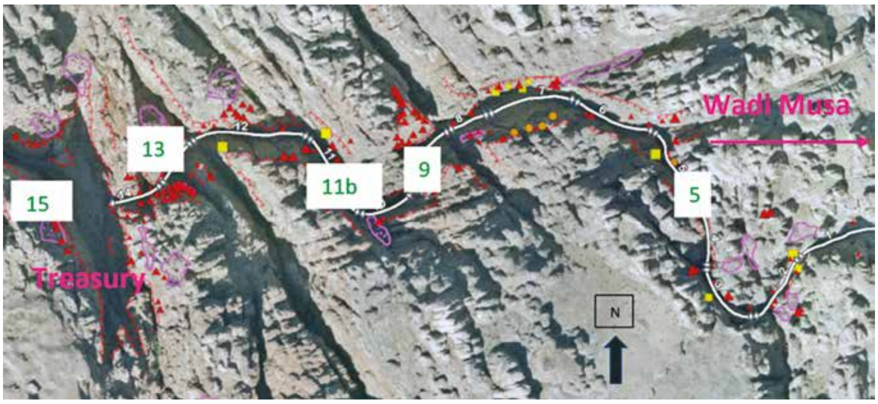

Fig. 10 – Sectors involved by consolidation works implemented in 2021 in the 'Siq'; the map reports the inventory of the potentially unstable blocks (points, squares, triangles) produced by ISPRA during the Phase I of the UNESCO 'Siq' Stability Project.

stability phenomena (Delmonaco *et al*., 2017a). In 2018, after a first consolidation of a block in the 'Siq' sector 9 (Fig. 9), the Phase IV of the project was devoted to rock slope consolidation works of large blocks as the most challenging and difficult engineering activity so far undertaken in the 'Siq' of Petra. In July 2019, a further on-site surveys using climbing techniques was performed by the whole project team (UNESCO, ISPRA, geologists and engineers) mainly in order to: a) complete the engineering geological survey and data collection; b) install geotechnical monitoring systems; finalize the project design of consolidation works for the selected areas. Therefore, the works were implemented in the sectors 5, 9, 11B, 13 and 15 (Treasury area) in January-March 2021 by OR.BA.RI. snc and Consolrocce srl under the supervision of ISPRA and based on design projects provided to UNESCO by the aforementioned companies (Fig. 10).

3.2. Engineering geological analysis

In this paper, a detailed description of consolidation of the block located in the sector 5 is reported; nevertheless, the consolidation works undertaken in the sectors 9, 11, 13 and 15, even if technically less complex, were indeed of fundamental importance for the reduction of rock fall and debris flow hazard in the 'Siq'. The sector 5 is located approximately 500 m from the main entrance of the Siq, on the N and right side of the canyon. Here the canyon has a NNW-SSE direction (canyon rock face direction) and is ca. 80 m high. The danger is represented by a large potentially unstable rock block characterized by the base placed at an elevation of approx.17 m and the top at ca. 43 m above the ground level of the Siq path. The rock block has a W slope face exposition. Due to the narrow distance between the 'Siq' slopes, in this area the solar irradiation is quite low. The total dimension of the block is ca.1000 m^3 (Fig. 11).

Lithologically, the block is composed by sandstone belonging to the middle part of the Umm Ishrinn formation. The rock presents horizontal layers and beds of variable thickness (from few cm up to 1 m) with variable degree of strength and weathering. The base of the block, composed by cm-thick sandstone layers, is softer and strongly weathered than the upper part due to wind erosion and thermal stress (Fig. 12). The bedding planes are horizontal, locally with an inclination of 5° towards East, N90°/5°.

The block is characterized by the following main joint systems: joint set K1 N250-N70/85, joint set K2 N340-N160/85 and the rock bedding N90/5 (Fig. 13). The intersection between perpendicular, vertical joints and the horizontal bedding creates prismatic columns. The block is delimitated by a vertical joint system. The three faces exposition of the block is approx. N250-N160-N340. The surveyed discontinuities system corresponds to the main and secondary regional tectonic structures (e.g. faults, joints) (Fig. 14).

A large joint (N250-N70/70-85)

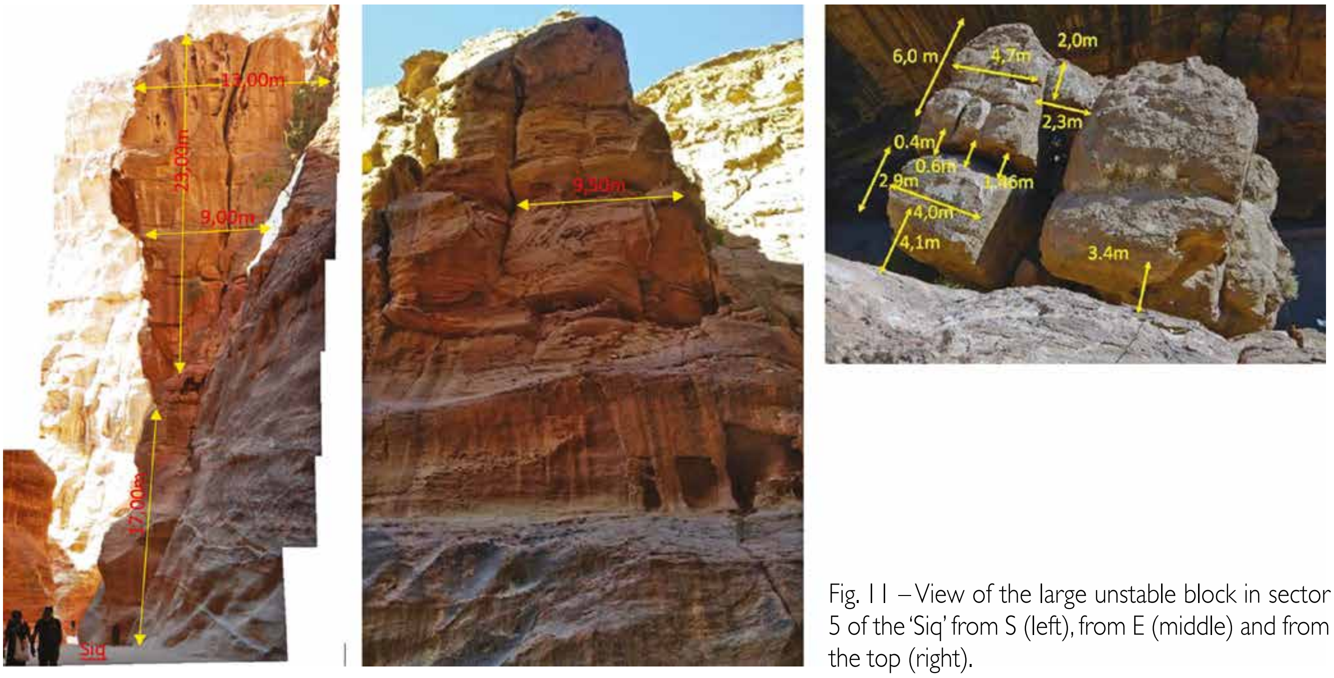

Fig. 11 – View of the large unstable block in sector 5 of the 'Siq' from S (left), from E (middle) and from the top (right).

Fig. 12 – Base of the large block located in the 'Siq', sector 5.

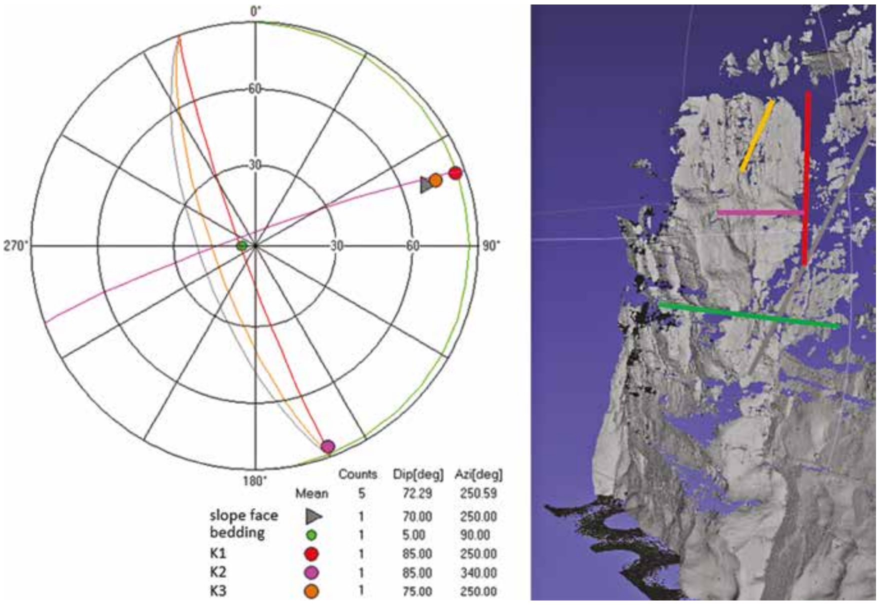

Fig. 13 – Stereoplot of the main discontinuities surveyed in the block of sector 5 (source laser scanner image: UNESCO/Zamani).

separates the block 5 from the rock slope. This sub-vertical joint is 4.10 m wide on the top of the block. South of block 5, the rock slope presents also an old sliding plane K1-1 (N250/70-80 (Fig. 15). The rock quality of the slope face can be classified as good.

The K1, K2 and K3 joint sets systems and the horizontal bedding divide the rock block 5 into five prismatic colums (a-e of Figure 16).

The Table 2 reports the main geotechnical and geomechanical data surveyed by ISPRA in the Phase I and during direct site surveys on the block carried out in 2019 where the main joint systems were also directly monitored through endo-

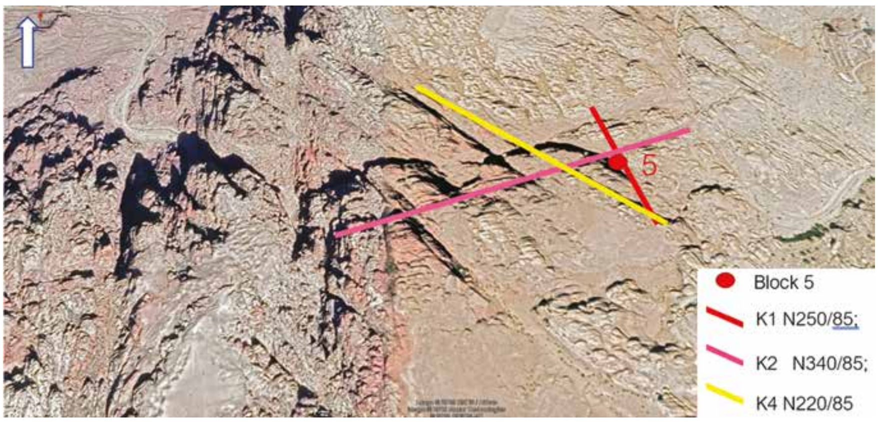

Fig. 14 – Orientation of the main discontinuities surveyed in the block of sector 5.

Fig. 15 – The arrow shows an old sliding plane surveyed S of block 5.

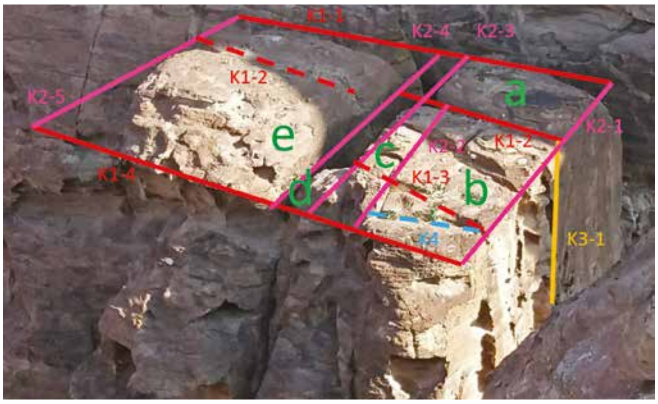

Fig. 16 – Separation of block 5 into five prismatic columnar-blocks (a-e).

Fig. 17 – Endoscope log in set K1-2 (left), jointmeter in K1-2 (right).

scope logs and jointmeter (Fig. 17 and 18).

From July 2019 to February 2021, the joint K2-4 was constantly monitored with a jointmeter and datalogger (Fig. 19). The graph shows the annual cyclical movement of the joint which is equal to 6 mm and a permanent displacement of ca. 1 mm. This movement is caused by the daily and seasonal thermal obscillations with the same trends previously shown in Figure 8. The direct monitoring of the large sub-vertical crack of block 5 undertaken in the period 2013-2016 also showed a permanent displacement of ca 2 mm. Over time, these movements can cause instability of the rock block.

A kinematic analysis for the assessment of potential failure type was performed for blocks 5a and 5b (which includes blocks 5b, 5c and 5d). The block 5e was considered as more stable and not included in the project. The joints K-1-1, K1-2, K2-1, K2-3, and K 3-1 are the perimeter faces of block 5a. The base of the block 5a is represented by the sliding plane K1-1 (N250-/70°-80°). The geological surveys and geomechanical

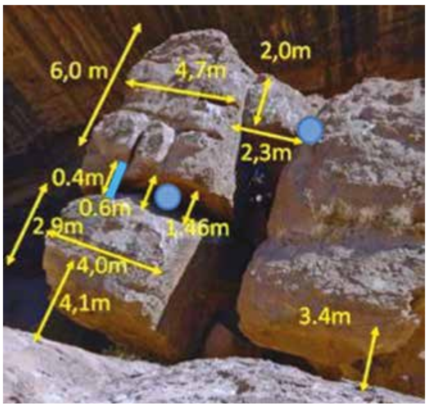

Fig. 18 – Location of jointmeter (blue line) and endoscopic logs (blue points) on block 5 (right).

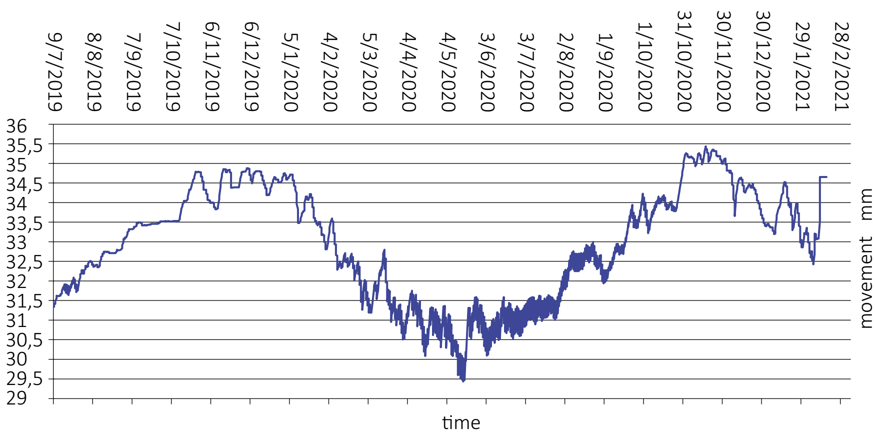

Fig. 19 – Trend of displacement of the large crack in block 5 monitored with a jointmeter (July 2019-February 2021).

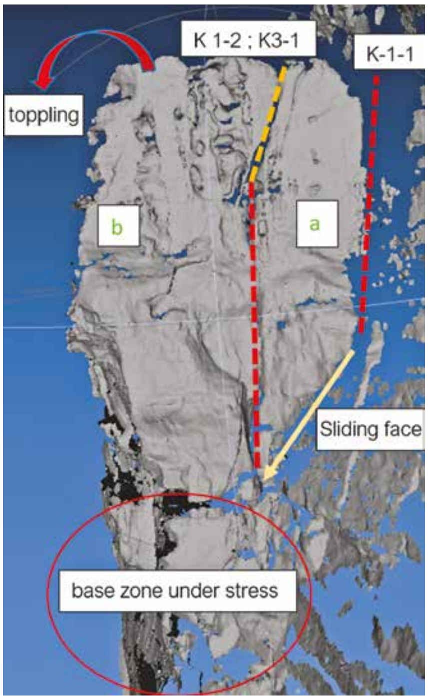

Fig. 20 – Potential failure types acting in the block 5 after kinematic analysis (3D laser scanning image from UNESCO-Zamani).

kinematic evaluations show that the block 5a could be destabilized by an initially sliding movement. The joint K1-2, K1-4, K2-1, K2-3, K 3-1 are the perimeter faces of block 5b. Along the base of the block 5b, a cm-wide vertical joints (N160°/340°-85°/90°) were detected. These joints are probably generated by the conversion of compression into tensile stress. The compression stress is provided by the weight of the upper prismatic column 5b. Kinematically, the block 5b could be destabilized by an initially toppling movement with direction N220 /N250. The blocks 5a and 5b were therefore classified as highly potentially unstable (Fig. 20).

3.3. Design phase

As an important assumption for the design phase, due to the lack of specific regulations in Jordan for rock slope consolidation works, the project design was undertaken according to the following Italian regulations and guidelines and Eurocodes:

- NTC2018;
- Eurocode 7;
- Eurocode 8;
- UNI EN 14490:2010 “soil nailing”;
- UNI EN 12715:2003 “injections”;
- UNI EN 1537 “anchor tie-rods”;
- AICAPP recommendations;
- UNI 11211-1÷4 Rockfall protective measures;
- UNI EN ISO 17746:2016 “Steel wire rope net panels and rolls — Definitions and specifications”;
- CIRIA – Rock netting systems – design, installation and whole-life management, 2018 reference manual.

In continuity with the consolidation works implemented in the previous Phase III, it was considered as fundamental to check the state and degree of maintenance of the structural elements, thus assessing the effectiveness and efficiency of the intervention, as well as of the aesthetical conditions of the works camouflage (e.g. ropes, nets) as another key aspect to take into account (Fig. 21).

The design phase of the consolidation works for each individual intervention has taken into account the complex geometries and variable volumes of the the blocks as well as their mutual interaction. This implies the choice of different consolidation technologies to be adopted and individually computed in order to optimize and calibrate the whole intervention. The meticulous analysis of the geometries, which are strictly related to the lithotype and geomechanical characteristics of the rock, allowed to proceed with a simplification of the volumetric distributions fully adherent to the reality and representative of the most probable kinematics. Consequently, any single intervention was designed and dimensioned according to the objective of consolidation, shape maintenance and masking of the visible structural elements.

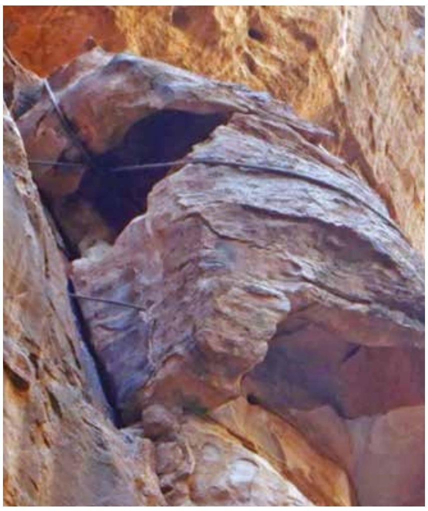

Fig. 21 – Rock block consolidated with anchored ropes in 2019 during the Phase III of the ‘Siq Stability Project’.

The executive design of the slope reinforcement works has been based on the approaches and recommendations available in the technical literature (Hoek and Bray, 1981; Barton and Bandis, 1982; Bustamante, 1985; Panet, 1987; Duffy, 1992; Giani, 1992; Nicot *et al.*, 2001; Ruegger *et al.*, 2001; Cravero *et al.*, 2004; Ferraiolo and Giacchetti, 2004; Sasiharan *et al.*, 2006; Oreste, 2009; Cargnel and Cargnel, 2011; AGI-AICAP 2012).

The use of the limit equilibrium software (SWEDGE® and ROCKPLANE®) was accompanied by “hand” calculations by which the reinforcing elements (nails or anchors, bindings) were computed.

As a general approach, the high cultural and scenic values of the ‘Siq’s were taken into account for the consolidation methods; barbicans and reinforced concrete ribs were excluded in all cases as well as any demolition of large volume of rocks since they belong to the natural and cultural heritage of the ‘Siq’ due to their unicity. The minimization of the visual impact of works was also considered in the design and implementation phases of the works. All the external structural elements (e.g. ropes, nets, head of anchors) where masked with different techniques. Also importantly, the continuous fruition and the passage of tourists in the working areas of the 'Siq' have been considered indispensable preconditions for the choice of the consolidation works and site safety measures.

The nailing was dimensioned for a total consolidation of geomechanical situations, while the cortical reinforcements were dimensioned to contain the release of superficial portions of the rock masses, where detected. The anchorage length of the bars is given by the sum of the foundation length (within the rock mass considered to be stable, so strength hierarchies were considered) and the free length. The free length was optimized on a case-by-case basis based on the size of the rock blocks, the morphology of the slope, and the parietal fractures present, which are very often of considerable thickness.

For individual blocks of smaller volumetry or where nailing is difficult due to the width of the fractures to the back of the rock bodies, it has been opted for resisting elements that are barely visible but effective for the objective, i.e., wire rope ligatures that envelop the unstable blocks and anchor into the stable rock mass with double spiroidal rope anchors.

The whole geometric shape of block 5 has been divided into two main blocks, block A and block B (pillar), both detached from the stable rock mass. Moreover, the block B has been divided into 3 distinct sectors (Fig. 22). The volumes of the single blocks are the following: block A/block 4: 150 m^3; block 1: 280 m^3; block 2: 350 m^3; block 3: 200 m^3; block B (total): 830 m^3.

In accordance with the general approach, it is assumed the consolidation of the block A has to be done by means of steel cables anchored to the stable mass since it could induce a negative thrust for the pillar. Then, for the consolidation of the pillar (block B), a mesh of deep anchor bars (portion 1 and 2) and (portion 3, where the risk of detachment of rocky elements on surface also remains) by high tensile strength steel wire rope net in addition to bindings and anchors were adopted. Consolidation steps as well have been planned to allow the highest safety conditions for operators and tourists during the works.

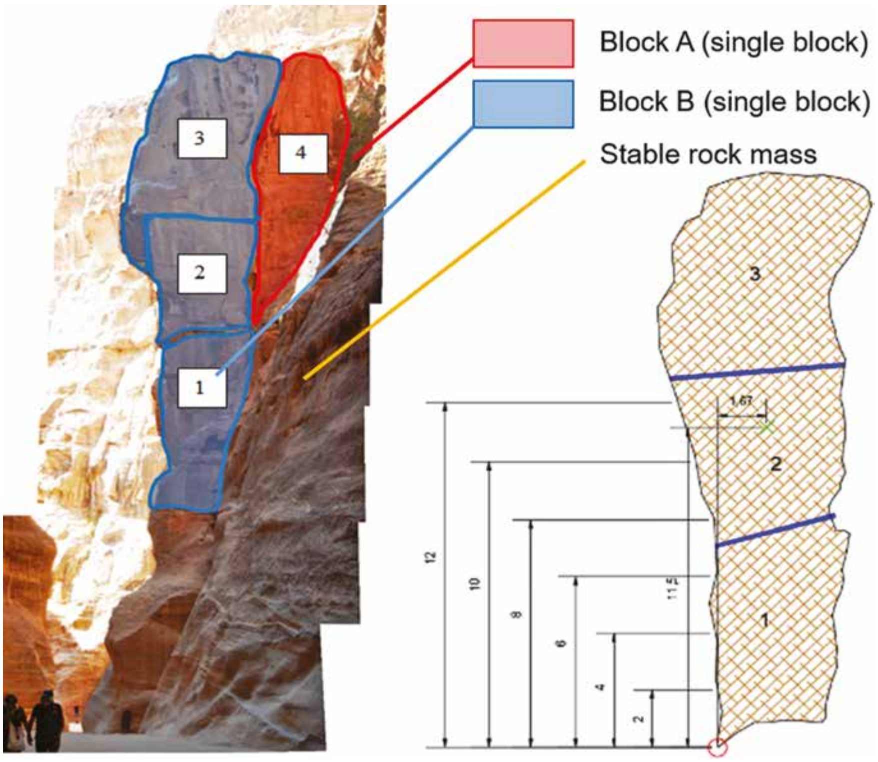

Fig. 22 – Scheme of block 5.

For block 5A subject to sliding, the mobilizing force was calculated according to the weight of the rock mass and the average inclination of the slope. A discontinuity friction angle of 41.75° was also taken into account to consider the effect of resistance to motion in the hypothesis of sliding trigger and nullification of the cohesion given by the rock bridges now existing.

Since some of the rock bars responsible for stabilizing the so-called 5B rocky mass also pass through the 5A block, we could count on their contribution for the stabilization of the rocky mass. As a precautionary measure, this contribution has not been taken into account in the verification, leaving only to bindings to counteract the destabilizing forces. From the analyses carried out, it is necessary to apply n.8 pairs of anchorages in double spiral rope ø16mm within perforation ø60mm of the length L=6m.

For the binding, steel wire ropes of diameter ø(min) 18 mm has been used in number of 2 ropes for each pair of anchors.

Under conservative conditions, in verifications conducted at equilibrium of the rigid body, only 3 m for each individual bar anchored in the solid rock have been considered. The anchors are provided in steel bar S950 / 1050 Ø32mm within a borehole Ø 90mm.

From the analyses carried out under the above assumptions, it follows that a mesh of bars 2m x 2m is necessary.

Taking into account the geometry, it was decided to create six or-

Fig. 23 – Construction of the protection net in the 'Siq'.

ders of bars with vertical spacing of 2m: the 3 lower lines, 9m long; the 2 intermediate lines, 12m long, and the upper line 15m considering that in the event of triggering instability due to toppling, the first and most stressed bars will be those above.

The steel chosen is high strength S950/1050, to have greater guarantees in case of unexpected shear stresses, which could be generated by seismic mobilization of the mass not in line with the installation of the anchors.

During the execution phase, it was also planned to put in place 4 bindings composed of steel ropes ø20mm connected to 4 pairs of anchorages in double spiral rope of 16mm within perforation ø(min) 60mm, 4.00m in length. These bindings, which are useful for the safety of workers, have not been taken into account in the calculation model, although they also have a consolidating effect.

In the planned configuration, a safety factor of FS = 1.35 is achieved.

3.4. Works implementation

The works have been initiated with the protection of the archaeological remains with sandbags and reinforced geotextile. The tourist passage was guaranteed by the construction of protective metal nets with wire ropes anchored on the two opposite sides of the canyon, consisting of wire mesh panels supporting double-twisted rock fall protection nets covered with geotextile (Figg. 23-24).

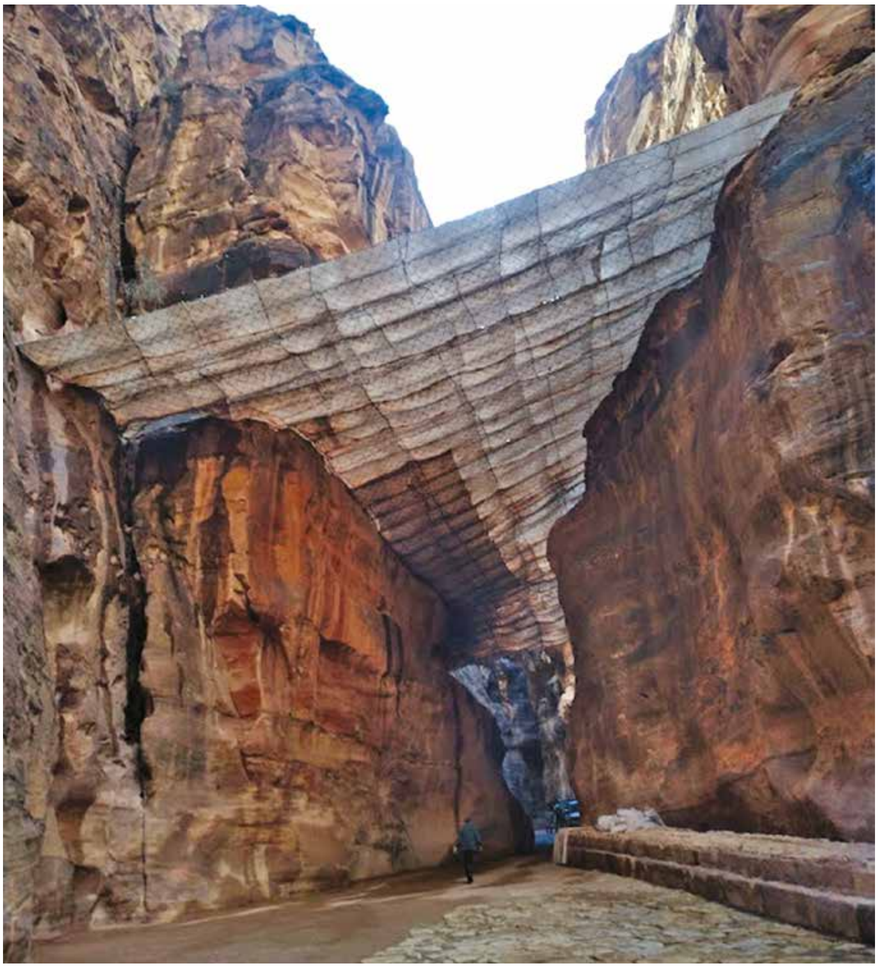

Fig. 24 – Final view of the protection net.

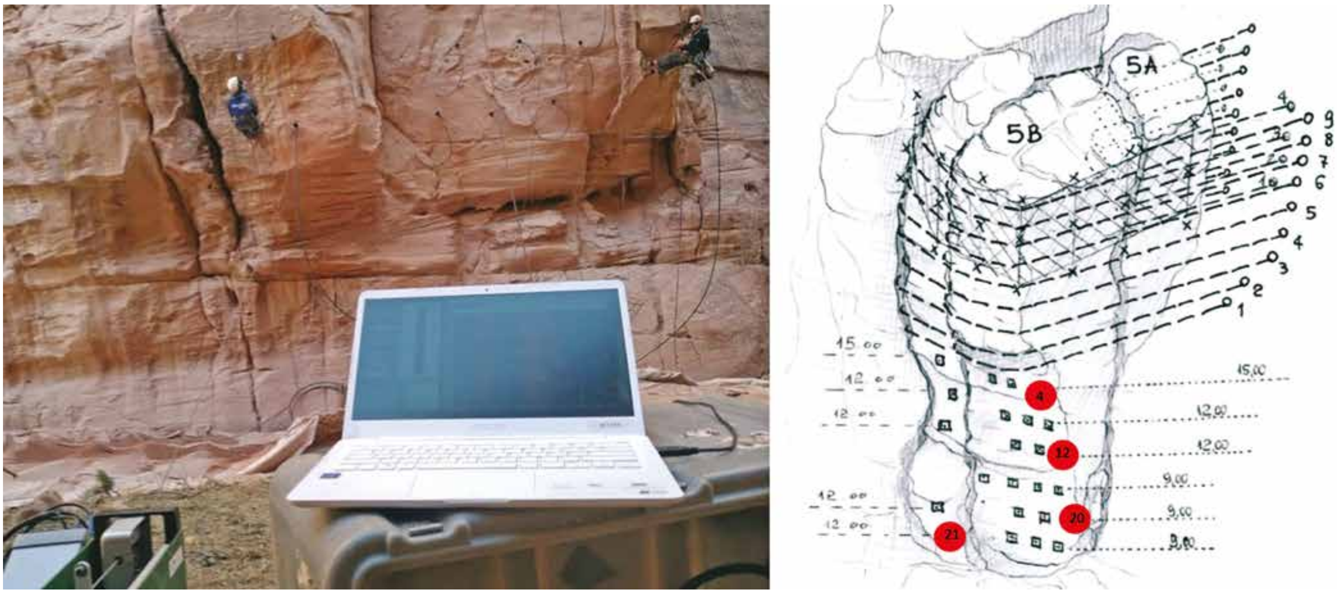

Fig. 25 – Real-time analysis with borehole optical televiewer, block 5. The red spots indicate the boreholes investigated (drawing by Elio Orlandi).

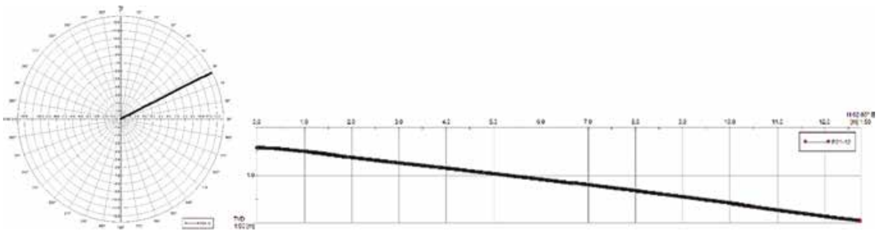

Fig. 26 – Orientation data, inclination and length of a borehole drilled in block 5.

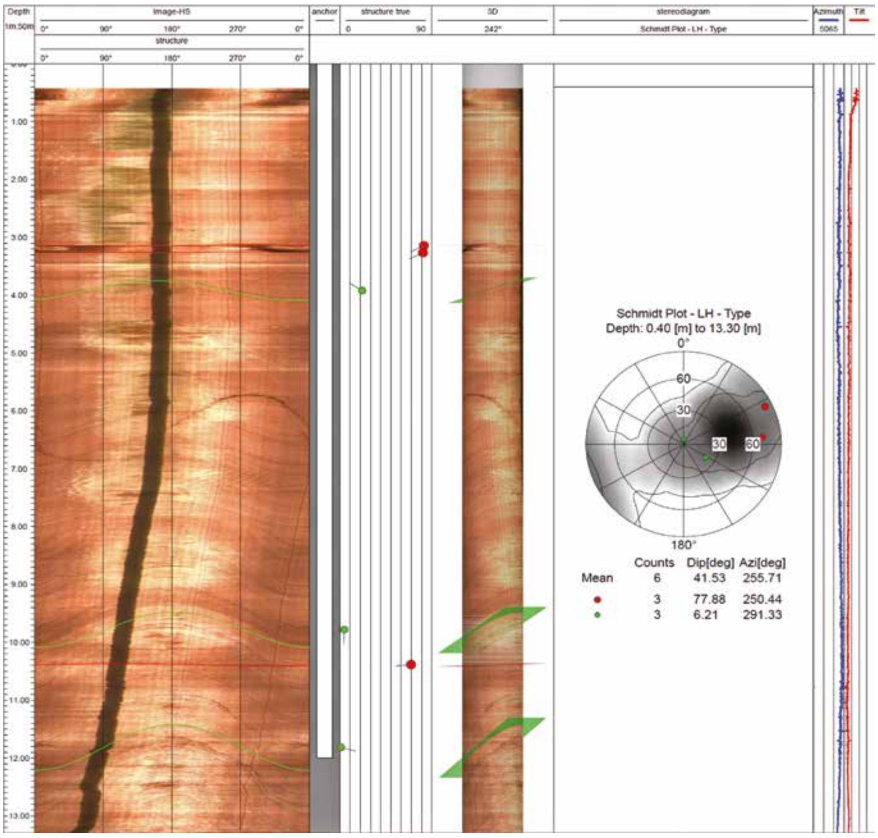

Fig. 27 – Borehole logging image.

The block 5A has been consolidated with 4 ropes, and the block 5B (the more unstable block) has been consolidated with 9 ropes. The base of the block was consolidated with 24 deep anchors.

During the drilling phase for the anchoring, the rock deep joints conditions have been analyzed in some boreholes through the borehole optical televiewer OBI™ (Figg. 25-28). This optical borehole imager generates a continuous true color image of the borehole wall via an optical imaging system using a downhole CCD camera that records the image of the borehole wall in a prism. A built in high precision orientation package incorporating a 3-axis magnetometer and 3-axis accelerometer allows orientation of the images to a global reference and determination of the borehole's azimuth and inclination. The tool is fully downhole digital and runs on standard wirelines. The geomechanical analysis of the oriented borehole image can be utilized to detect presence of discontinuities, thin beds and determination of bedding dip. The real-time analysis in the block 5 detected a deeper discontinuity in the rock mass, not visible from

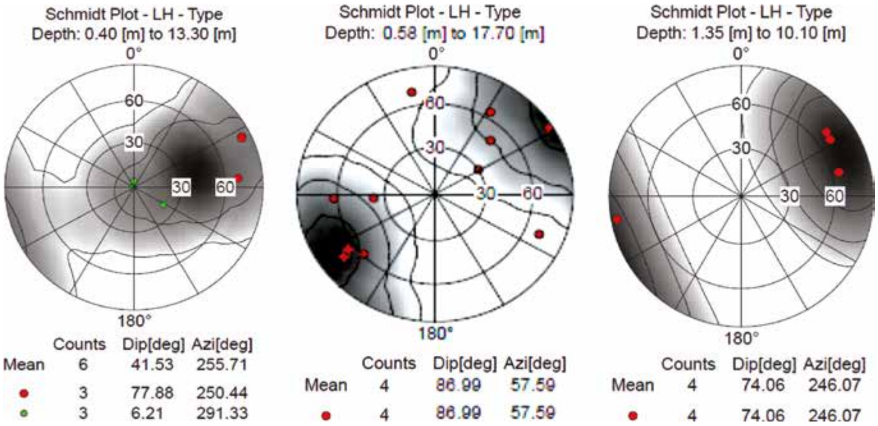

Fig. 28 – Stereoplot of joints (red spots) and bedding (green spots) detected with the optical televiewer.

outside. Due to this condition, it was decided to increase the depth of some boreholes and anchors in order to provide the highest safety conditions.

The borehole optical televiewer was also used to analyze the geo-structural conditions of the rock mass where a pull-out test was carried out (Shu *et al.*, 2005). The pull-out test resulted in deformation of the system grout/bar without rupture (Fig. 29).

The drilling operations for the anchors were monitored with a vibrometer (Fig. 30) which provided data showing a negligible disturbance for the rock mass.

The operation of camouflage of the anchors works in the block 5 included the coverage of the head of the anchors with mortar mixed with local sand (Figg. 31-32).


Fig. 29 – Pull-out test implemented in the 'Siq' of Petra.


Fig. 30 – Vibrometer installed in the block 5 during the drilling operations.

4. Discussion

The paper reports the results of slope consolidation works carried out in the 'Siq' of Petra, a UNESCO World Heritage site in the framework of the UNESCO 'Siq Stability Programme'. A brief summary of previous activities conducted in Petra in the last decade highlights the need by Jordanian relevant authorities to implement direct and indirect actions for the mitigation of rock fall and debris flow in the 'Siq' to reduce the risk for tourists and the unique cultural and natural heritage of the 'Siq'. The slope consolidation works implemented in the period 2019-2021 by Italian expert rock climbers, engineers and geologists represent the last and most challenging stage of a long-term involvement and investments from UNESCO and AICS. The project design included a systematic site geological analysis and use of innovative technologies (i.e. borehole logging analysis) for monitoring geostructural rock conditions utilized for the first time in slope anchoring operations. The project works included effective safety measures for the protection of the cultural heritage and tourists in Petra since all operations were carried out during the visit hours of the archaeological site. A special attention was also devoted as much as possible to the minimization of the visual impact of the works in order to preserve the natural aspect of the site. The slope consolidation works implemented in the 'Siq' of Petra represent a unique and successful

Fig. 31 – Head of anchor covered with mortar.

Fig. 32 – Final view of block 5 front after the consolidation works.

experience conducted in a UNESCO World Heritage site subject to landslide hazard which included not only the implementation of the slope works but also capacity building and training activities addressed to Jordanian technicians and workers. Finally, it is worth of consideration the need to proceed with further activities such as control and monitoring of other critical zones in the 'Siq' potentially subject to slope instability.

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